Status Report on R&D for SNAP/JDEM
February 2004

In November 2003, NASA and DOE announced an agreement to fund a Joint Dark Energy Mission (JDEM) with a competitive process to select a mission in 2006. We describe in this report the current objectives of the R&D program in light of the JDEM plan and provide a brief report on the current status of the R&D investigations. An external technical panel of space instrumentation and detector experts very recently reviewed the plan we are currently executing and that review was performed in the context of the JDEM white paper. This report follows the plan and recommendations from this recent review.

The SNAP science hinges on the reach to high redshift supernovae and precision weak lensing measurement only achievable in space. Realization of the science requires state-of-the-art photodetectors in the visible to near infrared (NIR) wavelengths (0.35 – 1.7 μm). A DOE review noted that this is "the most ambitious detector focal plane ever proposed, for ground or space." With the investments we are making in the R&D period, we can advance these devices into the enabling technologies required for the SNAP science program. If we fail to ready these technologies in time the science reach of SNAP will be compromised and its ability to successfully compete for JDEM will be seriously weakened. The recent technical review in Nov. 2003 by outside experts emphasized this point: "With the recent re-direction to JDEM, it is very important to re-focus and heavily emphasize work on advancing key technologies. Detectors and electronics are likely *the* highest risk area in the mission concept. The visible arrays, and especially the near-IR arrays, are not in the bag." To set the scale of this ambitious program, the IR system that we are proposing contains more devices than are currently deployed on ground-based systems. We realize that serious failure in the R&D program would result in significant loss of science or worse. Likely we would have to consider a much smaller focal plane with the potential elimination of wavebands (visible or infrared) and loss of the dark energy science of greatest interest.

The SNAP team has taken the advice of these review committees to heart, and has continued to refine and focus the R&D program. Instead of a Conceptual Design Report for a CD1 review conducted by DOE, our efforts are now focused on developing the science, the technologies, and the concepts in time for the JDEM Announcement of Opportunity, to be issued and competed by DOE and NASA. The overall scope of the R&D program has been refined to take into account the process by putting enhanced effort into simulations to understand various mission concept trade-offs. These studies will be key inputs to the JDEM Science Definition Team. We are carrying out an optimization across the total scientific mission, including the telescope, focal plane, and science simulation to establish scientifically driven requirements. This integrated approach to Dark Energy science is the focus for the SNAP R&D period.

Importance of SNAP R&D
Scientific need for compact, radiation tolerant, IR sensitive, accurate detectors
Can not accurately measure high redshift SNe with current detectors
Most complex focal plane ever fielded
More NIR detectors in SNAP than currently deployed in astronomy
Identified major program and high technical risk by reviewers
Identified major cost, schedule risk by reviewers
DOE project management guidelines for upfront investment
R&D difficult if not impossible to schedule or mandate outcome
Understanding of technology boundaries needed for science definition team
Simulation capabilities needed for science definition team
Maintenance of collaboration momentum and investment

Key enabling technologies that are being developed are as follows:

1. By developing smaller pixel sizes than previously possible in astronomical sensors we have been able to increase the field-of-view by a factor of 2.5. Thereby decreasing the time the mission needs to operate by the same factor.
2. Using our experience in radiation sensors we have greatly extended the current life of astronomical sensors from their one-year survival in high earth orbit.
3. By developing new infrared pixel sensors from InGaAs and HgCdTe substrates we have enabled the observation of the early universe before the time of cosmic acceleration.

It is in the very nature of this R&D that it takes years to develop a technology to the point that it can be used in a high-value experiment. It is also very hard to schedule or predict and, therefore, inappropriate to be performed in the full swing of a construction project.

The SNAP collaboration is very appreciative of the DOE's ongoing support for this R&D plan. Continuity in funding is extremely important to maintain the collaboration, its forward momentum, and the vitality of the technology programs. There are compelling reasons to maintain this ongoing support:

1) Project management guidelines developed in DOE and NASA emphasize the need for a well-understood cost (25% uncertainty) and schedule baseline before a project can be approved for a construction start. Investment in this activity has been shown to save money in the long run and to greatly improve the likelihood of completing on schedule and within

budget. A reasonable project funding profile must include early R&D monies to optimize the conceptual design and establish a credible cost and schedule baseline. SNAP's strong competitive position makes this early investment more, not less, important.

2) Detector development for the SNAP focal plane has been clearly identified as a major technical and schedule risk. If the detector development needed for SNAP does not proceed, the science goals are at risk. This R&D program is relevant for competing proposals, and for other complementary research investigations (see below for more details).
3) The SNAP collaboration consists of university and national laboratory groups, many of whom have committed institutional funding to leverage the DOE R&D funds. Interruption in the R&D funding will disrupt the collaboration and result in wasted effort, making it much more difficult to maintain the project's momentum and focus, and undermining its credibility.
4) Participation in the science definition process for JDEM will require the use of the extensive simulation capabilities that are being developed.

In the next sections we describe the R&D program in greater detail and the status of the research.

Detector R&D

The recent SNAP internal technical review conducted in November 2003 brought together a committee including many respected experts in space instrumentation. In their report they made the following recommendation: "This is a very ambitious focal plane concept, involving unprecedented pixel counts for a space mission. Some promising initial thinking has been done regarding the very large numbers of devices which need to be screened, characterized and selected. The present plan to demonstrate performance and producibility is good; however, once performance is established, the project should rapidly develop and demonstrate high-volume test plans and capabilities." This affirms our view that the sensor R&D is the highest priority and must include a detailed plan for production and testing of the full complement of sensors. Failure to meet these R&D goals will diminish SNAP's scientific impact. The supernova yield that can be collected within a fixed observing program, for example, is a strong function of the achieved signal to noise ratio, and the reach in redshift depends on a corresponding range in wavelength enabled by the new IR sensors.

Visible Sensors (LBNL, Yale, Michigan, Indiana)

All SNe of interest to SNAP have useful light in the range of 0.35-1.0 μm. Weak lensing surveys are also interested in this bandpass. Weak lensing and less so SNe require good spatial control of the photon generated charge at the pixel size level. Silicon based CCDs are the preferred detectors in this regime due to their 100% pixel fill factor, good linearity and large dynamic range. Good response out to 1.0 μm to overlap the NIR detectors is not typical for CCDs. Also, space use of CCDs, while obviously successful, has been troublesome due to their deterioration after exposure to very modest radiation doses. The LBNL CCDs are uniquely suited for SNAP and other space missions. Their thickness provides the required extended red response, over-depletion provides good control of charge diffusion allowing the sensible use of small pixels leading to a reduced focal plane area for the same pixel count, and radiation tolerance because they are based on HEP-proven high resistivity, n-type silicon.

LBNL CCDs are optimal for the SNAP focal plane and very much in demand by ground-based astronomers as well. (Requests number in the 100's.) Their radiation tolerance, extended response into the near-infrared and small point-spread function are the features that set them apart from traditional astronomical science-grade CCDs. LBNL CCDs are also well-suited for some of the ambitious large ground-based focal planes that have recently been proposed, such as the FNAL CTIO camera and the LSST focal plane.

The overall goal of this R&D program is to develop the SNAP CCD, to demonstrate that it will meet SNAP requirements, deploy the devices in astronomical settings, and to industrialize the production so that the quantities needed for SNAP will be readily available with a well-understood cost and schedule. A side benefit will be the availability of packaged LBNL CCDs for ground-based astronomy, where long-term operation will help validate their suitability for a space mission.

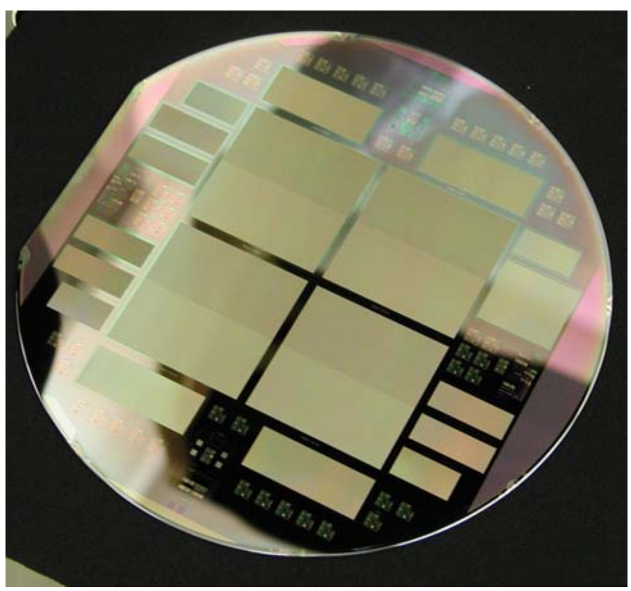


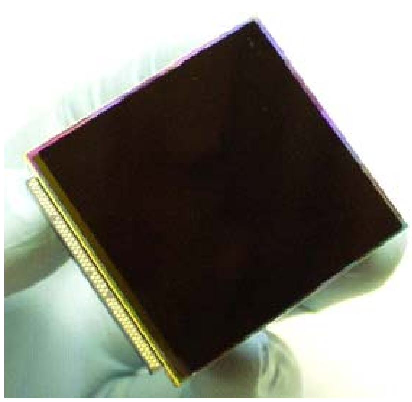
Figure 1. LBNL designed 150 mm wafer partially fabricated at DALSA Semiconductor. The four large square CCDs are SNAP devices, 3.5k x 3.5k, 10.5 μm pixels.

Device characterization, such as quantum efficiency, dark current, readnoise, point spread function, and radiation testing had been performed over the last several years. The radiation testing plan is not complete. The next phase will begin this summer with cold, powered irradiation at the Yale van de Graaff.

The first CCDs specifically designed for the SNAP focal plane are just coming back from DALSA Semiconductor. Two non-thinned devices have been tested and are working well. We are concentrating on the high depletion voltage robustness of these parts. Two wafers have been thinned and backside finished. The first 200 μm thick SNAP CCD is about to be packaged and tested. An additional 32 wafers are available. The present SNAP wafers have four minor design variants. After the depletion voltage studies, additional lots with a single design will be fabricated. In parallel, we are developing packaging techniques that will be compatible with the SNAP focal plane requirements and robust enough to withstand the shock and vibrations of launch. An additional area of R&D is the development of suitable fixed filters.

NIR (Michigan, Cal Tech, UCLA, JPL)

NIR detectors with wavelength response from 0.9–1.7 μm complement the LBNL CCDs. The high-side cutoff is sufficient to identify the SiII line of Type Ia SNe at z=1.7, yet low enough to be blind to thermal photons form the warm telescope. Commercially available materials can have good response in this range, but detailed performance characteristics for astronomical use have not been achieved. The areas of concern are simultaneous achievement of good quantum efficiency, low dark current, and low readnoise. As noted by the November 2003 Internal Review, “1.7 μm cutoff HgCdTe technology…is clearly not yet established for the mission…The team needs to actively work with the supplier(s), and, armed with good test data, to carefully direct and focus work to improve the technology.” After demonstrating good performance on a few detectors, we still need to demonstrate that this is now a stable process for a large production run.



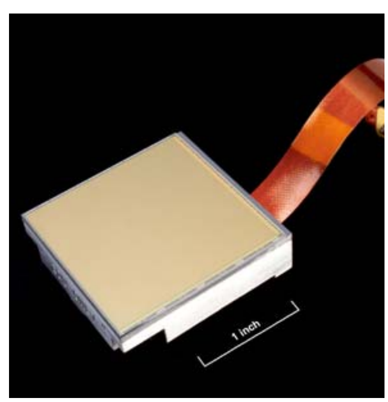


Figure 2. 2k x 2k HgCdTe detectors from Rockwell (left) and Raytheon (right).

We have contracted for the production of the HgCdTe detectors from the two leading vendors and InGaAs detectors from one vendor. For HgCdTe, crystal growth techniques, stoichiometry, and layer stacking are being explored. The first HgCdTe sensors fabricated for SNAP are now available for testing and the remainder in various stages of completion. Cursory parts testing at the HgCdTe vendors already indicates that further iteration of detector development will be required. We are waiting for our own detailed tests before deciding how to proceed. Parts from two or more vendors will be characterized over the next three months. To evaluate these parts, we have established three test sites within the SNAP collaboration. U. Michigan and Cal Tech will test HgCdTe and NASA JPL will test the InGaAs. All three sites have built up testing infrastructure and Michigan and Cal Tech are already testing non-SNAP devices to characterize and validate their test equipment. All sites have dewars and readout electronics in place. For practice, Michigan and Cal Tech have readout devices without the photodetector material in place. JPL will be at this state in a month. All sites will be able to study cosmetic defects, quantum efficiency, dark current, readnoise and readnoise reduction via over-sampling. Michigan has commissioned a pinhole projector to study intra- and inter-pixel response.

Simulation and Computing (LBNL, U Penn, FNAL, Michigan, Cal Tech, Marseilles)

Simulation is the link between the SNAP science goals on the one side and the establishment of minimum instrument performance requirements. To date, these requirements and optimization studies have come from analytical techniques such as the Fisher Matrix formalism for error propagation. Specific questions were answered by very focused studies and calculations. While this has served us well, some of the issues are so complex and inter-dependent that a full Monte Carlo simulation of the astrophysical and instrumental effects is required. We now have an end-to-end Monte Carlo that generates supernovae based on a few model parameters, propagates the light according to a given choice of cosmology, includes astrophysical effects such as dust extinction and weak lensing, and incorporates instrumental effects such as K-corrections.

In the developing simulation, instrumental effects are parameterized in real-world terms of read noise, dark currents, point spread function, and calibration errors. For comparison with ground-based telescopes, the Monte Carlo also includes an atmospheric model with air mass and seeing effects. The result of the Monte Carlo is a Hubble diagram of corrected magnitude versus redshift. A cosmological fitter then extracts cosmological parameters from the simulated Hubble diagram for comparison with the generated cosmology. The Monte Carlo will be extended to other space-based concepts to allow a fully science requirements driven optimization of SNAP and will be an important part of our contribution to the JDEM science definition team.

The costs and schedules for developing computing infrastructure for large ground and space based surveys have been very large. Since this will need to be incorporated into JDEM, research into historical cost drivers for existing projects will be done during the R&D period. Already, we have experimented with the recycling of code from the STScI HST and the FNAL SDSS pipelines.

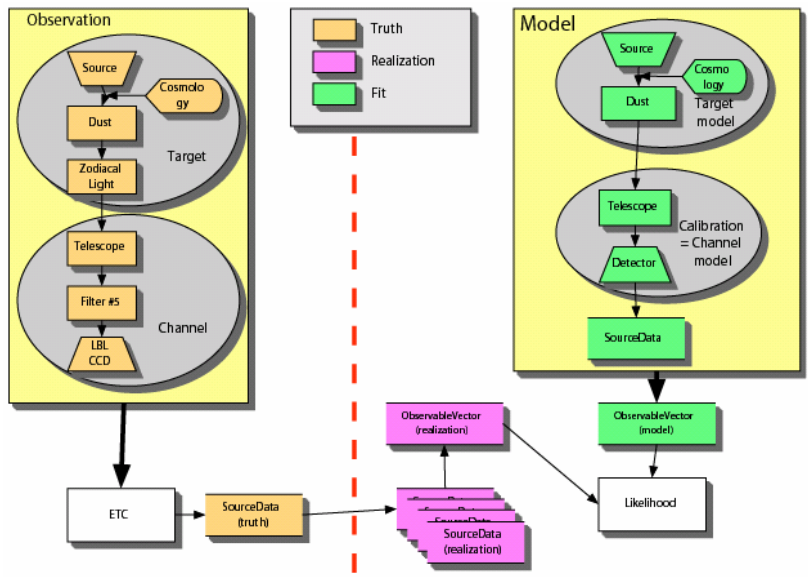


Figure 3. Top: The grand scheme of a typical simulation run has a mirrored structure. First there is the simulation phase, to the left of the red line, where *truth* is generated. A *realization* of the data and noise are created and thrown "over the wall" to the right side. Calibration and Analysis consist of a new set of models of the sources and instruments, which generate the *fit*, expected data to be compared with the realization.

Electronics R&D (LBNL, FNAL, SLAC)

The SNAP electronics R&D effort has two main goals. The first is the early development of an ASIC to read out and digitize the CCD signals. The second major goal of the SNAP electronics R&D program is a detailed conceptual design of the electronics architecture, which will serve as the basis for a cost and schedule estimate. Currently, CCD's for spaceflight are read-out by an electronics subassembly the size of a breadbox. Given the large number of devices on the SNAP focal plane this is not an option and we are applying our expertise in electronics miniaturization through ASIC development.

The focal plane detectors all generate very low level signals with large dynamic range. To mitigate cross talk and EMI pickup, we are developing electronics to intercept these signals at the detectors. A side benefit is a reduction in the cable plant complexity and volume. To achieve this, we are first concentrating on the more challenging CCD readout by developing low voltage CMOS circuits operated at the detector temperature of 140 K. We can later apply the knowledge gained to the readout of the NIR detectors if a commercial solution in development proves unsatisfactory.

The ASIC R&D program is already well advanced, with the successful fabrication and test of a front-end test chip, the CRIC. The ADC design is complete and the complete chip (CRIC2) will be submitted in March, 2004. Demonstration of CRIC operation at 140 K and exposed to radiation has been demonstrated. A modified version of this chip could also be used for the NIR detector readout, if the ASIC development in progress at Rockwell Scientific does not succeed or does not meet SNAP needs.

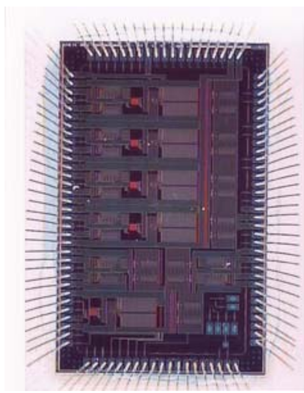


Figure 4. Left, a micrograph of the CRIC ASIC. Right, image acquired with an LBNL CCD and CRIC circuit both operated at 140 K.

Reviewers have been very enthusiastic about this project, as in the recent Internal Review report: “LBNL’s CRIC and A/D efforts are ‘top rate’, and very well conceived and executed. The effort indicates lots of expertise, and understanding of requirements. When fully proven, these elements should be very valuable to the project (and to others). “In fact, significant interest in the SNAP ASIC has already been shown by others and there is enthusiasm for a “photons to bits” package in which an LBNL CCD is packaged together with an ASIC.

Beyond the front-end electronics, there is a large detector and instrument control system and a large volume of data to be compressed, buffered, and telemetered to ground. The electronics system architecture studies include conceptual design studies for delivering the many clock and control signals and bias voltages required by the CCDs and NIR detectors, for the Instrument Control Unit that controls the focal plane, and for the Mass Memory System used to store data for several days between downlinks. This detailed conceptual design must satisfy the criteria of radiation tolerance and reliability, low power and minimum weight required for a space mission. While engineered designs are in general not required, it must be sufficiently fleshed out to provide the basis for a credible cost and schedule.

Calibration (LBNL, FNAL, Indiana, LANL, RIT, SSL, STScI)

SNAP has challenging spectrophotometric calibration requirements over an unprecedented wavelength span. The basic concern is to understand the instrument response to incoming light as a function of wavelength, intensity, environment and time. This requires development of instrument calibration concepts (in flight and ground methods) and absolute color calibration procedures with understanding of error budge and flow down.

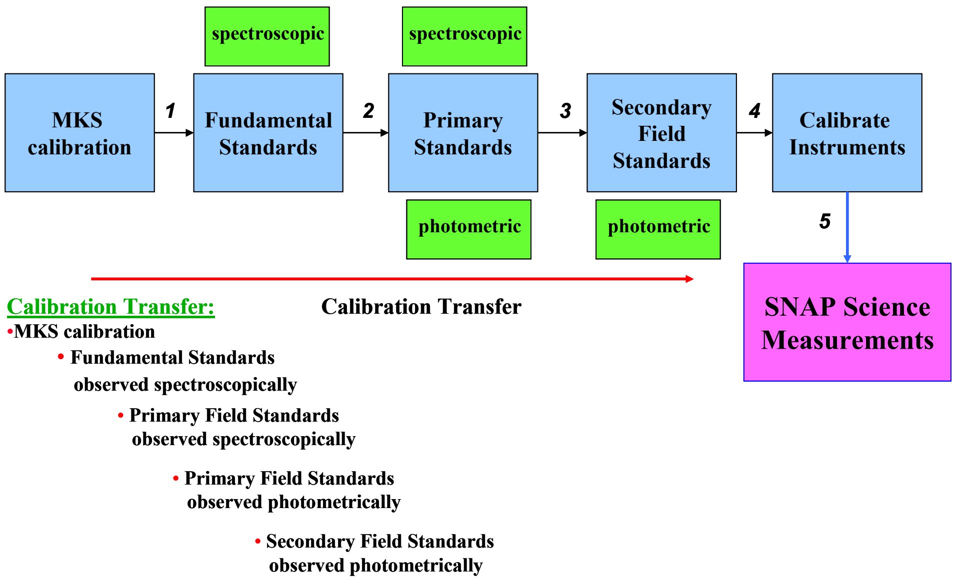


Figure 5. Standard star calibration flow: how to get from SNAP measurements to mks units.

Existing standard stars are very bright relative to the SNe of interest to SNAP. How to measure the former with SNAP and carry forward the calibration to weak sources is challenging. A detailed calibration plan is being formed incorporating NIST black bodies, known standard stars, and developing new ones of different brightness and spectral types. Pre-launch observation may be required and in fact SNAP collaborators, often in partnership with others, will be using existing DOE and NASA facilities to start the development of a new standard star network. A viable overall calibration plan must be part of the SNAP concept.

Calibration also impacts in-flight hardware and observation strategies. Impacts of temporal changes in the telescope optics, detector response, and filter band centers and band passes will feed into requirements. How to monitor these on-orbit is impacting the focal plane and filter concept, generating requirements of other instrument hardware such as lamps and shutter performance.

Observation time for flat-fields and standard stars will come at the expense of SNe observation. Therefore a well developed calibration plan needs to be part of the SNAP conceptual design.

System Engineering (SSL, LBNL, Michigan)

The layout of the detectors on the focal plane and how they are used is coupled with the telescope design and certain spacecraft performance goals. There is a synergy of telescope designers, spacecraft requirements development, and detector performance studies that must be maintained during the R&D period.

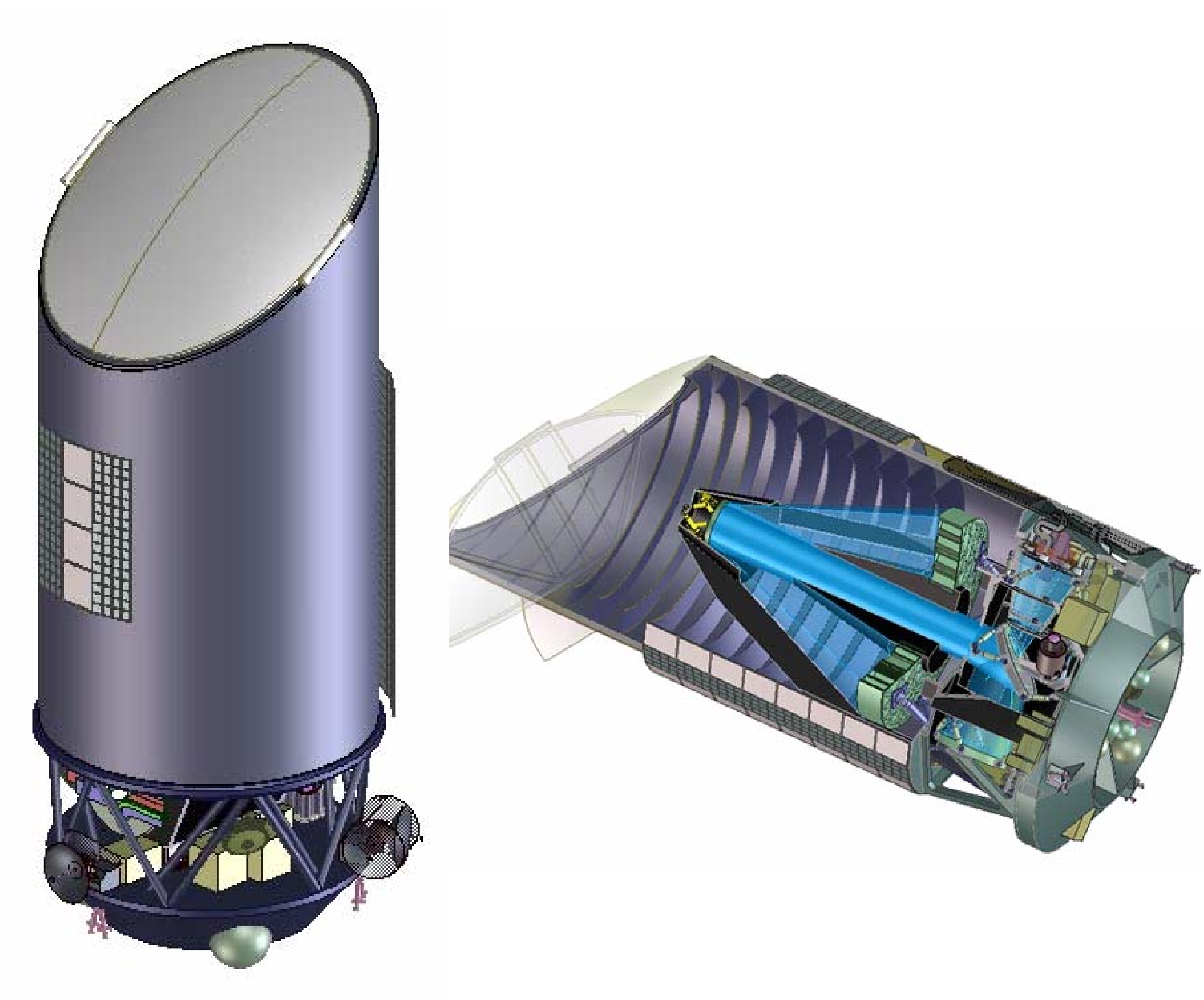


Figure 6. Fully integrated reference design provided by SNAP System Engineering covering all aspects of telescope, focal plane, and spacecraft integration. This is used to explore interplay of various components such as baffles, optics, and stray light or telescope support structure and spacecraft point stability performance interaction.

The telescope fabrication cycle and final integration and test are the dominant schedule and cost drivers for the project. Because the telescope affects the overall spacecraft packaging and drives some of the focal plane detector requirements, its design is highly mature. This maturity is allowing detailed analysis of fabrication and testing approaches from which project cost and schedules can be derived. The telescope optics obviously impacts the focal plane size and layout and the observation strategy. Iterations of the focal plane filter strategies couple tightly with the telescope optics. The R&D effort on direct deposition of filters onto focal plane detectors is motivated by reducing demands on telescope stray light and optical distortion compensation.

Spacecraft pointing and pointing stability, focal plane detector spatial response, and satellite observation strategy are coupled. Non-uniform spatial detector response can be overcome with the concept of dithering where multiple exposures are precisely displaced from each other to sample different areas of pixels. During an exposure, the image must be maintained steady at a level determined by telescope optics design and photometric accuracy requirements. This generates requirements on the spacecraft attitude control system, or, conversely, the performance that can reasonably be achieved drives the telescope optics, shutter motion disturbance, detector spatial response requirements, and the overall observation strategy.

Another area of overall system design is thermal control. To fully benefit from the stable environment of space, the telescope and focal plane need to be in a very stable thermal environment. Again, a team working coherently at this time on the telescope, spacecraft, and focal plane will produce a mission concept for the JDEM with supportable and viable mass, volume, cost and schedule estimates.

Conceptual Design, Overall Cost and Schedule Development

Detailed cost and scheduling requires a well-developed conceptual design. To put this in place and carry out the cost and schedule exercise requires a significant investment in engineering, including engineers with experience in space missions. We have assembled a strong team of engineers from LBNL and Space Sciences Lab as the core system engineering group, charged with developing a detailed conceptual design at the appropriate level for JDEM, and carrying out trade studies to optimize the performance at minimum cost. In addition, physicists and engineers at FNAL, SLAC, U. Michigan, Indiana U., Johns Hopkins, U. Pennsylvania, and Yale, many supported at least partially on internal funds, are contributing to detailed conceptual design and simulation.

SNAP R&D Benefits

Beyond SNAP, the technologies being developed have already filtered out into new instruments and applications including medical imaging and national defense applications. Although the most immediate usess are found in astronomical telescopes, the potential of the technology will find its way into other applications.

CCDs

- Keck Telescope
- Kitt Peak (NOAO)
- Licensed to DigiRad for medical imaging
- US Air Force evaluating for space use
- Potential DOE funded projects – FNAL CTIO camera, LSST
- General ground based telescopes (inquiries totaling ~200 2kx4k devices)
- X-ray detection at LLNL NIF.
- Synchrotron light source detectors – protein crystallography
- Future x-ray satellite – Japan
- Industrial use for Raman spectroscopy

Near infrared

- Ground based astronomy applications for short wavelength cutoff material – either HgCdTe or InGaAs.

Electronics

- CCD ASIC approach of interest to present and future ground based telescopes – Palomar, FNAL CTIO, LSST.
- Variant for massively parallel CCD readout at synchrotron light source.